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Measurements of the Dimensions and Doppler Flow Velocities of the Aorta, Main Pulmonary Artery, Ductus Arteriosus, and Branch Pulmonary Artery in the Normal Human Fetus -a Preliminary Study on the Flow Distribution-†

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= Abstract = **In order to assess the growth and flow distribution of the great arteries and their major branches in the human fetal heart, a prospective fetal echocardiographic study on 127 pregnant women was performed. The vascular dimensions and Doppler average velocities of the aorta, main pulmonary artery, branch pulmonary artery and ductus arteriosus were measured from videotapes. Dimension ratios and average velocity ratios were calculated only when both values for comparison were measured in the same examination. The flow volumes of the aorta and main pulmonary artery were calculated when possible. The measured and calculated values were correlated with the gestational period.**

The vessel diameters and average velocities in each site increased linearly from gestational period of 15 weeks to 40 weeks. The diameter ratio of the main pulmonary artery to the aorta increased slightly from 1.13 at gestational age of 15 weeks to 1.31 at term. The diameter ratio of the ductus arteriosus to the branch pulmonary artery was 1.28(±0.18) and did not change with gestational period. The average velocity ratio between the main pulmonary artery and the aorta was 0.88(±0.24) and the ratio between the ductus and branch pulmonary artery was 1.71 (±0.54) and these ratios were not significant when compared to fetal growth. The calculated flow volumes of the aorta and the main pulmonary artery increased polynominally with increasing gestation. The flow ratio between the main pulmonary artery and the aorta was about 1.37. The ductal and branch pulmonary arterial flows were not calculated. However the flow ratio between the ductus arteriosus and one branch pulmonary artery was estimated by the product of (diameter ratio)^2 x (average velocity ratio) between two sites, which was 2.8.

In the human fetus, the relative size of aortic and pulmonary pathways and the flow distribution seem to be different from the results obtained from animal studies.

Key Words: *Fetal echocardiography, Human fetus, Flow distribution, Vessel dimension, Doppler*

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INTRODUCTION

Our present knowledge of fetal circulation is derived mainly from studies carried out on animal models particularly in lambs. (Rudolph and Heymann 1970; Rudolph 1985) In the fetal lamb, the right ventricle ejects about 60-65 % and the left ventricle only 35-40% of combined ventricular output. The lung receives 7-8% of combined output and the remaining 55% of combined output ejected by the right ventricle passes through the ductus arteriosus. Patterns of blood flow and flow distribution indices derived from animal studies have subsequently been extrapolated to the human fetus.

However studies on the human fetus have suggested that flow distribution of the human fetus might be different from results obtained from animal experiments. In the human fetus, right ventricular output is about 1.3 times greater than the left ventricular output, which is somewhat different from animal experiments. (Kenny *et al*. 1986; De Smedt *et al*. 1987) Furthermore a study on the dimensions of the aortic and pulmonary pathways in the human fetus showed that branch pulmonary arterial dimension was relatively large and arterial ductal dimension was relatively small. (Angelini *et al*. 1988)

In order to assess flow distribution in a fetus noninvasively, diameters and Doppler average velocities of small fetal vessels should be measured accurately. Recent studies on fetal animals have shown that the ultrasound measurement of dimensions and the flow volumes from vessels of more than 4mm in diameter are indeed accurate. (Veille *et al*. 1988; Veille *et al*. 1989; Schmidt *et al* 1991) Eik-Nes *et al*. (1982) studied the accuracy of ultrasound measurement of flow volumes in the human fetus and discussed the sources of errors in flow measurement. Since the vessel diameter is squared for flow calculation, the vessel area is most sensitive to error and the smaller the vessel is, the greater the margin of error will be. Considering the resolution power of currently available machines, one should be most careful with the blood flow quantification if the vessel diameter is below 5mm, for example the human fetal ductus arteriosus and branch pulmonary artery, because the margin of error in dimension measurement would be too great. However the diameter ratio of similar sized very small fetal vessels measured under a similar conditions may be less subject to error because of a similar magnitude of errors in both measurements. Therefore the flow ratio of the ductus areteriosus to the branch pulmonary artery may be assessed by the product of (dimension ratio)^2 x (average velocity ratio).

The purposes of this study were : 1) to assess the growth of the aorta, main pulmonary artery , ductus arteriosus, and branch pulmonary artery and also assess the relative size of the vessels with fetal growth. 2) to measure the average velocities of Doppler waveforms from each site and relate them with gestational period 3) to calculate flow volumes passing through the aorta and main pulmonary artery, and to get some insight into the flow distribution of the right ventricular output in the human fetus.

MATERIALS AND METHODS

Pregnant women referred to the echocardiographic laboratory of Seoul National University Children's Hospital for fetal echocardiography were prospectively assessed for two years. The inclusion criteria for this study were: 1) pregnant women without major illnesses such as diabetes mellitus, hypertension, eclampsia etc. which might affect fetal well- being, 2) no major fetal diseases or anomalies, and 3) singleton fetus. After delivery, all babies were examined by one of the authors and no babies had any significant anomalies or diseases.

One hundred and twenty seven pregnant women participated in the study. All participants underwent two or more echocardiographic examinations at least 4 weeks apart. A total of 260 fetal echocardiographic examinations was performed and 79 of them were excluded due to difficulties in measurement. One hundred and eighty one examinations, which permitted at least one measurement, were analyzed.

Ultrasound examinations were performed in supine or semisitting position and an Advanced Technology Laboratories Ultramark 8 was used. The structure of the fetal heart was examined with 5.0 M Hz annular transducer and a systematic cross-sectional echocardio graphic examination of the fetal heart was performed to exclude any structural abnormality. After the fetal heart was found to be normal, studies were carried out to obtain crosssectional images for the dimension measurement of the aorta, main pulmonary artery,

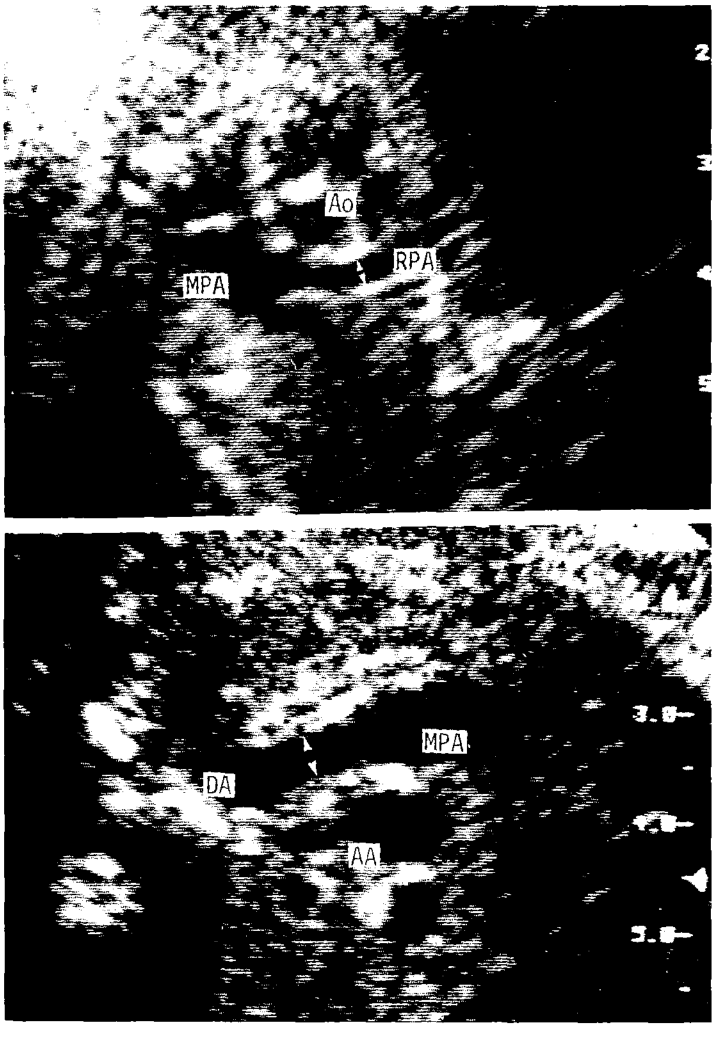

Fig. 1. Upper panel : The short axis image of the fetal heart shows the main pulmonary artery, right pulmonary artery, and aorta. The measurement site of right pulmonary arterial diameter is indicated by arrowheads. Lower panel : The horizontal image of fetal upper thorax shows the aortic arch and ductal arch side by side. The narrowest site along the arterial duct was measured as shown by arrowheads. AA: aortic arch, Ao: aorta, DA: descending aorta, MPA: main pulmonary artery, RPA: right pulmonary artery

right and left pulmonary artery and ductus arteriosus and also to get Doppler spectral waveforms from the same sites.

For the dimension measurement, efforts were taken to obtain clear zoomed images of the vascular structures and to align the measurement site in the axial resolution. Satisfactory images were recorded by videotape and analyzed later. The aorta and main pulmonary artery were measured at the valve annulus. The right and left pulmonary artery were measured slightly distal from the branch point on the short axis images and ductal dimensions were measured on the horizontal images of the fetal upper thorax and the narrowest site along the ductus arteriosus was used as the ductal dimension. (Fig. 1) Dimensions were measured from inner wall to inner wall in frozen cross sectional images when the vessel distended maximally during systole. Measurement was performed using built in software program of the machine and caliper works in 0.1mm steps. Measurement was repeated in three different frames and averaged. The measured values of the right and left pulmonary artery were analyzed together as no significant differences were found by non-paired t testing between two groups. ($p>0.05$)

For pulsed Doppler study, a 5.0 or 3.0 M Hz mechanical transducer was used. Doppler study was performed when the fetus was not moving or breathing. Doppler studies in cases of fetal tachycardia or bradycardia were excluded. The sample volume size was 1.5mm and a wall filter of 100 Hz was used in most cases. The "angle rotate" was used when the insonation angle was less than 30 degrees and Doppler study was abandoned if the insonation angle was more than 30 degrees. In most studies, insonation angles were less than 20 degrees. Doppler sample volumes were placed at or just superior to the valve annulus for the aorta and main pulmonary artery. For the Doppler studies of the right and left pulmonary artery, Doppler sample volumes were placed slightly distal to the branch point but in some cases, sample volumes were placed more distally to avoid signals from the surrounding structures. For the ductus arteriosus, the sample volume was placed at the narrowest area along the ductus arteriosus initially and then moved back and forth until the maximum velocity was recorded as a ductal waveform. All satisfactory waveforms were recorded on a videotape and analyzed later. The built-in software program was used for Doppler measurement of average velocity and heart rate. For the average velocity, tracings were made in the middle of the darkest area. Five Doppler waveforms with clear envelopes were measured and averaged.

From the diameters and average velocities in each examination, the following values were calculated. 1) dimension ratios between the aorta and main pulmonary artery and between the ductus and branch pulmonary artery: A dimension ratio was calculated when both sites for comparison were measured in the same examination. The dimension ratio between the aorta and main pulmonary artery was calculated in 60 examinations and the ratio between the ductus and branch pulmonary artery in 41 examinations. 2) average velocity ratios between the aorta and main pulmonary artery and between the ductus and branch pulmonary artery: an average velocity ratio was computed when both sites for comparison were measured. The average velocity ratio between the aorta and main pulmonary artery was calculated in 54 examinations and the ratio between the ductus and branch pulmonary artery in 36 examinations 3) flow volume: Flow volumes of the aorta and main pulmonary artery were calculated when both dimensions and the average velocity were obtained using an equation of flow volume (ml/min) = 1/4 diameter^2 x average velocity (cm/sec) x 60. 4) flow volume ratio: main pulmonary artery/aorta flow ratio was computed from 29 examinations in which aortic and pulmonary arterial flow were calculated simultaneously. Ductus/branch pulmonary artery flow ratio was deduced from the product of (dimension ratio)^2 x (average velocity ratio).

Vascular dimensions, average velocities, and the flow volume of aorta and main pulmonary artery were correlated with gestational period and the model which best fit the calculated value was determined using the SAS statistical package. The dimension ratios, average velocity ratios, and flow ratio between aorta and main pulmonary artery were expressed as mean ± (standard deviation) and were correlated with gestational period to see if these ratios changed with fetal growth. A p value of $<$ 0.05 was considered significant.

To assess intraobserver and interobserver variabilities, 60 measurements of diameter were repeated by the same and a second observer, each unware of previous results. Variability was expressed as difference from the mean of the two results in percent of the mean. The mean values and standard deviations of the variability percentage were calculated.

RESULTS

The number of examinations and measurements in each gestational interval is shown in table 1.

Table 1. The Number of studies and measurements in each gestational interval

Gestational period(weeks)	<21	21-25	26-30	>31	total
No of fetuses studied	42	51	46	42	181
No of measurements					
Ao dimension	22	27	24	20	93
Ao average vel	14	24	22	14	74
Ao flow	7	15	11	9	42
MPA dimension	17	35	26	26	104
MPA average vel	20	31	32	17	100
MPA flow	9	19	20	12	60
Br PA dimension	8	21	21	22	72
Br PA average vel	7	29	27	15	78
Ductus dimension	6	19	20	20	65
Ductus average vel	3	13	23	21	60

Ao:aorta, Br PA: branch pulmonary artery, MPA: main pulmonary artery, vel: velocity

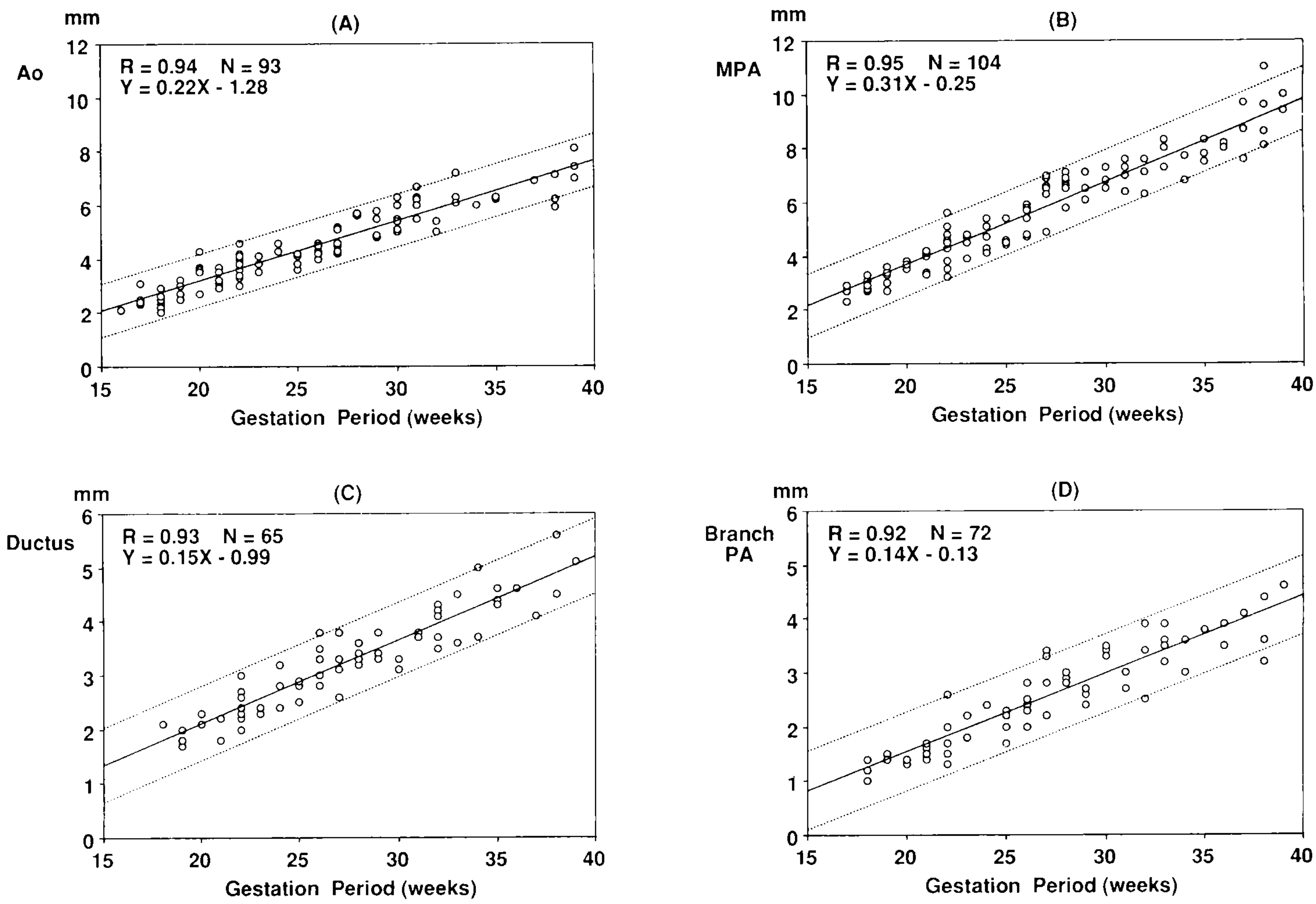

Fig. 2. Vessel diameters plotted against gestational age. Regression lines (solid line) and 5% and 95% confidence limits (broken line) are superimposed.
Ao: aorta, MPA: main pulmonary artery, PA: pulmonary artery. The same abbreviations are used in Fig. 3,4,5,6 and 7.

The relation between vascular dimension and gestational period is shown in Fig. 2. The vessel dimension at each site increased linearly from a gestation period of 15 weeks to 40 weeks. The dimension ratio of the main pulmonary artery to the aorta increased slightly from 1.13 at gestational age of 15 weeks to 1.31 at gestational age of 40 weeks. The diameter ratio of the ductus arteriosus to branch pulmonary artery was 1.28(±0.18) and did not change with advancing gestation.

The minute distance (cm, average velocity x 60) at each site increased linearly with increasing gestation. (Fig. 3) Individual values of minute distance showed a wide scatter particularly those of the ductus arteriosus and branch pulmonary artery. The average velocity ratio between the main pulmonary artery and aorta was 0.88(±0.24) and the ratio between the ductus and branch pulmonary artery was 1.71 (±0.54) and these ratios were not significant when compared to fetal growth.

The relation between flow volume of the aorta and main pulmonary artery and gestational period is shown in Fig. 4. The flow of each vessel increased significantly with fetal growth. The best fitting curve for the flow in each site versus gestational period was flow = a x gestation period^2 + b x gestation period. The flow ratio between the main pulmonary artery and aorta is shown in Fig. 5 and the ratio was 1.37 in average.

The flow ratio of the ductus to one branch pulmonary artery was deduced from the product of (dimension ratio)^2 X (average velocity ratio) and was 1.28 x 1.28 x 1.71(2.8). Accord-

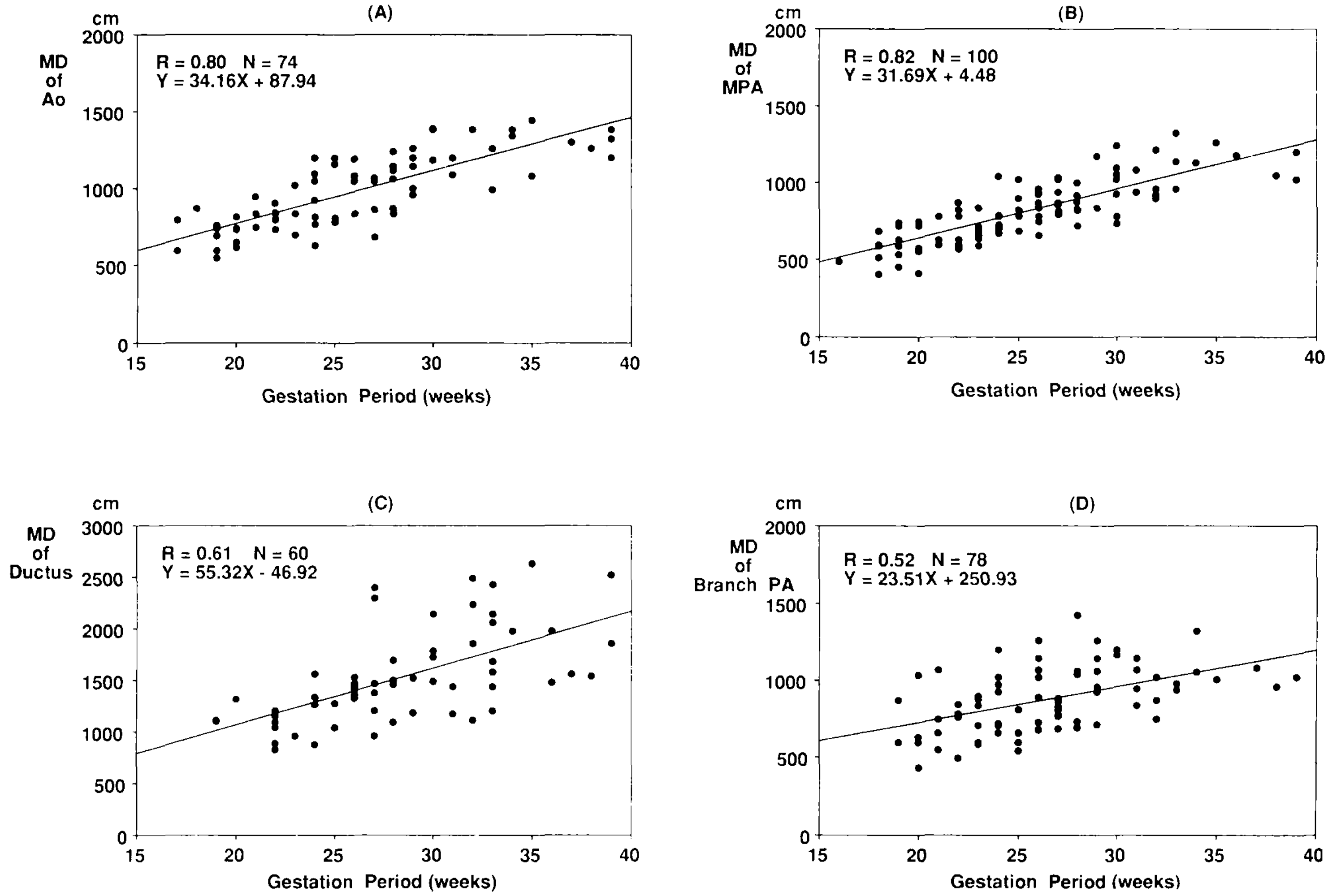

Fig. 3. Minute distances plotted against gestational age.
MD: minute distance

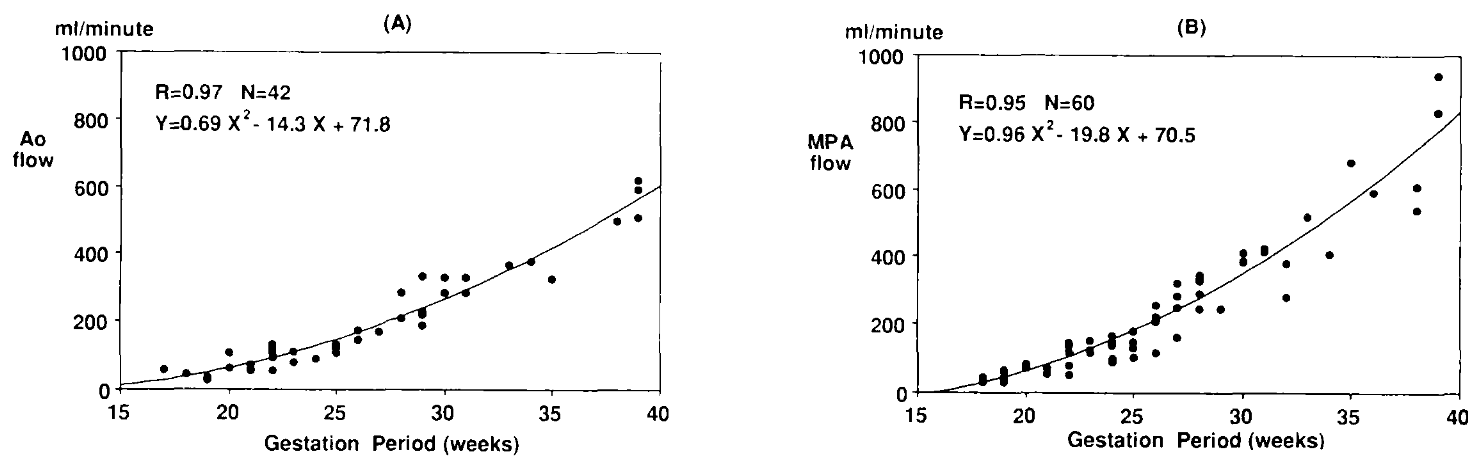

Fig. 4. Calculated flow volumes plotted against gestational age.

ingly about 60% of right ventricular output went through the ductus arteriosus and about 40% went to the lungs.

Intraobserver variability of dimension measurement was 2. 97% (±2.2) and interobserver variability was 3.02% (±2.4).

DISCUSSION

In order to assess the growth and function of the human fetal heart, ultrasound examination has been used to measure dimensions (Sahn *et al.* 1980; Allan *et al.* 1982) and to cal-

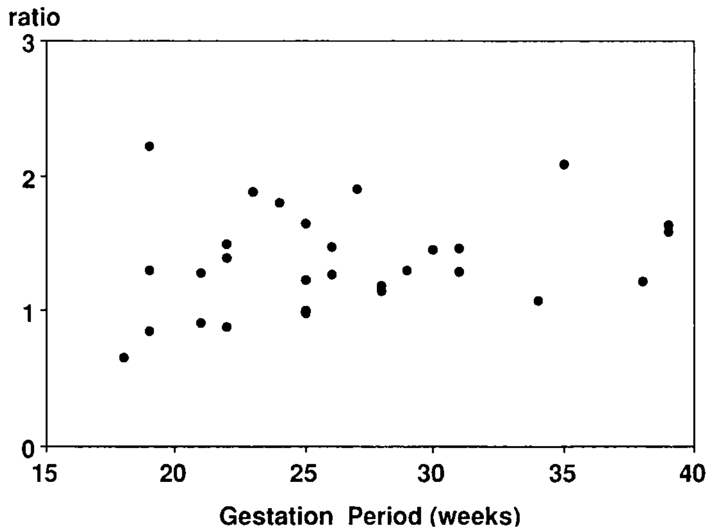

Fig. 5. The flow ratio of MPA/Ao plotted against gesational age.

culate flow volumes. (Kenny *et al.* 1986; De Smedt *et al.* 1987) Although the accuracy of these measurements in the human fetus is not known, recent animal fetal studies showed that ultrasound measurement of cardiovascular dimensions and Doppler echocardiographic flow measurement are accurate. (Veille *et al.* 1988; Veille *et al.* 1989; Schmidt *et al.* 1991)

The measurement of the dimensions of the vessels is the first and the most important step for flow calculations. As the size of the fetal vessels are generally smaller, extreme care should be taken for recording and measurement. The measurement site should be aligned in the axial resolution and the expanded and zoomed images are preferable for measurement. In order to measure the dimensions of the very small vessels whose diameters are less than 4mm, higher frequency transducers (over 7.5 M Hz) should be used and dimension from the leading edge to leading edge may be more accurate. (Koik *et al.* 1989) However higher frequency transducers do not have enough penetration power for routine transabdominal fetal echocardiography and the proximal leading edge is not always identifiable. In this study, vascular dimensions were measured from inner wall to inner wall and therefore, theoretically, measured values from inner wall to inner wall were smaller than actual dimensions by the resolution power of the machine, which is 0.6mm in this study. The margin of error of 0.6mm is too great for the vessels whose diameters range from 1mm to 5mm such as the ductus arteriosus and branch pulmonary artery. This is why we did not attempt to calculate the flow of the ductus and branch pulmonary artery. However this systemic error would not have much effect on the rate of growth of the vessels because nearly the same amount of error applied to all the measurements. Likewise the dimension ratios between measured values of similar sized vessels would not be different significantly from the ratio of actual values. Assuming that the true dimension of the ductus is 3.5mm and that of the branch pulmonary artery is 3.0mm. If the magnitude of errors in both measurements are equal (,which is not always the case) e.g. 0.6mm, the measured dimensions would be smaller than the true dimensions by 0.6mm. Then the dimension ratio of ductus branch pulmonary artery from measured values is 1.21. The ratio of true dimensions is 1.16 and there is 5% difference between measured and true values. Therefore the flow ratio between ductus and branch pulmonary artery estimated from the dimension ratio^2 x average velocity ratio would be reasonably accurate.

As suggested by Eik-Nes *et al.* (1982), another important source of error for the flow measurement is the insonation angle and it is very important to minimize the insonation angle. Optimal position for dimension measurement is the worst position for Doppler study. However the fetus often moves during the course of the examinations and it is not uncommon to get successful images for dimension and Doppler waveforms for average velocity. Another consideration for Doppler study may be that the sample volume size is relatively large for the small sizes of the fetal vessels and it is not uncommon to have Doppler signals from the surrounding structures(Sahn 1985), but the characteristic shape of Doppler waveforms from each site helps identify the origin of superimposed signals and minor adjustment of sample location or minor tilting of the transducer was enough to get clear signals(Choi *et al.* 1991).

One of the most important differences between clinical human fetal study and experimental animal study may be the temporal variation of the human fetus. The human fetus often moves and breathes and heart rate varies widely and changes in the physiologic condition may have some effect on the vascular dimension and Doppler values. (Rizzo *et al.* 1990; Indik and Reed 1990) In this study, Doppler examinations were performed when the fetus was not moving or breathing. Cases of extreme tachycardia or bradycardia were also excluded. In spite of these technical considerations, some fetuses showed variability in the height of Doppler waveforms without apparent reason. This kind of spontaneous temporal variation could have contributed to the scattering of measured Doppler values.

In the human fetus, the diameters of the aorta and main pulmonary artery were measured by many authors (Sahn *et al.* 1980; Allan *et al.* 1982; Kenny *et al.* 1986; Cartier *et al.* 1987) and all the studies showed linear growth of the aorta and main pulmonary artery with increasing gestational period. However actual values were somewhat different depending on the measurement method. Kenny *et al.* (1986) used the same measurement method as our study and the results of both studies were quite similar. The growth of the ductus arteriosus and branch pulmonary artery has not been reported as far as we know and this study showed that the diameters of these small fetal vessels increased linearly with increasing gestational period.

Angelini *et al.* (1988) measured the diameters of the aortic and pulmonary pathways using pathologic and clinical materials in the human fetus and showed that the size of the right and left pulmonary artery was relatively large and ductal size was relatively small which was confirmed by our observation.

Previous studies (Kenny *et al.* 1986; De Smedt *et al.* 1987) and this study showed that, in the human fetus, the right ventricular output is about 1.3 - 1.4 times larger than the left ventricular output, which is somewhat different from the results obtained from animal experiment. The other indices of flow distribution of the human fetus may also be different from the results of animal study and this study showed that, in the human fetus, the proportion of flow to the lungs was much higher and the proportion of flow through the ductus arteriosus was much lower than the results reported in fetal lamb studies.

Although small fetal vessels such as the ductus arteriosus and the right and left pulmonary artery can be visualized by cross-sectional echocardiography, the size of these vessels was too small for their dimensions to be measured accurately by currently available machines. Technical advances to improve resolution power and further studies on the effect of fetal physiologic changes on the fetal cardiovascular system seem necessary. Ultrasound with Doppler is the only currently available tool to explore the fetal cardivascular system in the human fetus and more knowledge about the human fetal cardiovascular system may be gained through ultrasound and Doppler examinations.

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